Challenges in dynamics & control for nanosatellites

Astronet-II Final Meeting
Steve Greenland
From nanopower...

Telemetry & switching

Batteries

Electric power system

Structures

Solar arrays

Modular platform concept

One-stop shop

Attitude control

to nanoplatforms
2010: Enabling downstream

1st Scottish Space Symposium

1. Standardised, modular, and reusable building blocks for satellite development
2. Rapid assessment of plausible design points and quick look mission feasibility
3. Low cost entry technologies to facilitate a stepped entry into systems development
2010: Enabling downstream
1st Scottish Space Symposium

4. Scalability and flexibility in building blocks for later customisation to mission

5. Growing opportunities for collaboration, in-orbit demonstration, and launch

6. Simplify operational interfaces and overheads with cost-effective spin-in technology
UKube approach

Defined as a **collaboration** across UK engaging with all parts of the space community.

**UK CubeSat**

*New Technology Innovation*

- **Industry**
- **Universities**
- **Payload x6**
- **Platform x2**
- **Test**
- **Launch x2**

**CubeSat Design, Build and Launch Knowledge Exchange and Training**

*Increased access to Space for UK researchers*

**“New” Universities and Industry**

Concepts will be developed by conventional means as well as CubeSat Payload
Broadcasts
Video Archive
Please standby for live feed...
Operations performed

- Receipt of health beacon
- Estimation of tracking TLEs and object identification
- Receipt and processing of telemetry packets
- Uplink command capability
- Very low spin rates since deployment
- Operation of the redundant communications
- Reports of beacon active over world
- Downlink of large data transfer from onboard
- Platform systems check-out
- Workaround for primary downlink blocking uplink
- Upgrades to ground station to compensate
- All payloads exercised
- Initial images captured and radiation damage performed
- Patches developed to partially mitigate RF grounding EMI issues
Impact

- Due to market driven growth and facilitated by our products and the experience of UKube-1, Clyde Space is now engaged in development of production of over 30 satellites.
- We have a new challenge: sustainable growth.
A capability to deliver

- We have a high quality skills base within engineering and manufacturing.
- ISO9001:2008 accredited Product Assurance process that is based on the ECSS guidelines.
- ESA qualified assembly technicians and inspectors.
- Experienced staff base; both home grown and incorporating SSTL, ESA, Thales, QinetiQ.
- End to end nanosatellite systems as prime, system integrator, subcontractor, etc.
- CubeSat sub-system technologies; over 1800 units sold with over 300 operational years on orbit.
- CubeSat products are complimented by a range of larger small satellite subsystems.
Where we are

• Past and ongoing engineering challenges
• Looking forward
  – Where we see the market heading
  – Future challenges for us in (astro)dynamics & control
• Enabling engagement for rapid realisation of novel nanosatellite concepts
• Conclusions
• Progression of ADCS capability
• Development of the uPPT product
• Deorbit constraints and sail
• Understanding UKube motion
Progression of infrastructure

Cakestand Mk I

ADCS Testbed (magnetic + airbearing)

Hardware in loop

Rate Cyros
Sun Sensor
Magnetometer
Star Tracker
GPS
Horizon Sensor

Attitude Estimation (EKF) (UKF)
Detumbling
Manuevering

Microgravity-on-Demand 1/2011 1120/P513D1L raw video
© 2011 JA. Terms of use: creativecommons.org/licenses/by-vn/3.0
## ADCS Systems

<table>
<thead>
<tr>
<th></th>
<th>Motherboard</th>
<th>Single Wheel</th>
<th>Orthogonal Wheel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Actuators</strong></td>
<td>6xMTQ</td>
<td>6xMTQ, 1xRW</td>
<td>MTQ, 3xRW</td>
</tr>
<tr>
<td><strong>Typical sensors</strong></td>
<td>MFS, Gyro, CSS</td>
<td>MFS, Gyro, FSS Horizon, Star</td>
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</tr>
<tr>
<td><strong>Detumble</strong></td>
<td>Y</td>
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<td>Y</td>
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<tr>
<td><strong>Nadir pointing (2-s)</strong></td>
<td>+/- 5 deg</td>
<td>+/- 1 deg</td>
<td>+/- 0.1 deg (target)</td>
</tr>
<tr>
<td><strong>Sun pointing (2-s)</strong></td>
<td>+/- 5 deg</td>
<td>+/- 1 deg</td>
<td>+/- 0.1 deg (target)</td>
</tr>
<tr>
<td><strong>Full 3-axis</strong></td>
<td>N</td>
<td>N</td>
<td>Y</td>
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Hardware-in-the-loop

- ADCS on board software can be developed and tested in the loop with Matlab/Simulink.
- Allows rapid prototyping and evaluation of ADCS algorithms.
- The ADCS board receive/send input/output to the simulation by using serial interface.
- Ideal for industry, research and education, especially with ADCS testbed v2.0.
ADCS HIL Simulator: Nadir Pointing Mission

Mission Requirement
- Nadir Pointing over North Pole
- Pointing Accuracy < 5 deg

Sensor
- GPS
- 2 Static Horizon Sensor
- 4 Coarse Sun Sensor
- 2-Magnetometer
- 3 Single Axis Gyros

Actuators
- 1-Axis RW
- 3-Axis MTQ

ADCS daughter Board with 2-Static Horizon Sensors and 1-Axis RW

ADCS Board

Gyroscopic Stabilization
Attitude Control
HIL Simulation: Nadir Pointing

Orbit:
Semi-major axis = 6963 Km
eccentricity = 0
inclination = 97.7 deg
ADCS HIL Simulator: Nadir Pointing Mission

Detumbling: B-dot control Law

In this phase only MTM readings and MTQ are used

Initial Angular velocity

\[ \omega_{sc} = [10, -10, 10] \text{deg/s} \]

Final Angular velocity

\[ \omega_{sc} = [0.34, 0.66, 0.08] \text{deg/s} \]
Nadir Pointing: The ADCS estimates the sc attitude using EKF with sensor fusion algorithm

Initial Pointing Error

\[ \theta_e = 175 \text{deg} \]

Final Pointing Error

\[ \theta_e < 5 \text{deg} \]
ADCS HIL Simulator: Sun Pointing

Mission Requirements
- Sun Pointing < 1 deg
- Maneuver speed > 2deg/s

Sensor
- GPS
- 1 Fine Sun Sensor
- 1 Star Tracker
- 4 Coarse Sun Sensor
- 2 Magnetometer
- 3 Single Axis Gyros

Actuators
- 3-Axis RWs
- 3-Axis MTQ

Attitude Control
RW Momentum Management
3-Axis RWs
3-Axis RWs daughter board
ADCS Board
HIL Simulator: Sun Pointing

Orbit:
Semi-major axis = 7078 Km
eccentricity = 0
inclination = 79 deg
ADCS HIL Simulator: Sun Pointing

Sun Pointing Maneuver: Attitude estimation using EKF with sensor fusion algorithm. Attitude control using 3-Axis RWs and MTQ for momentum management.

Rotation angle $\approx 130 \text{ deg}$

Maneuver time < 90 s

Pointing accuracy < 1 deg

![Graph showing pointing accuracy over time with specific values for time and rotation angle.]
ADCS HIL Simulation – Magnetometers Calibration

Performance analysis of calibration procedure to remove effect of bias, misalignment, scaling factor and compensate noise

Before calibration

After calibration
ADCS HIL Simulation – RW Characterization

Analysis of zero-crossing effect on system performance
ADCS HIL Simulation – Sensor Interferences

Analysis of the cross-interference between actuators and sensors to drive ADCS design

High RW speed causes jitter that can interfere with gyros readings and reduce mission accuracy

These effect can be easily analyse and compensate by ad-hoc ADCS design
• Progression of ADCS capability
• Development of the uPPT product
• Deorbit constraints and sail
• Understanding UKube motion
Achieving low thrust

- Developing a 15 kV spark plug requires
  - 1 shot power supplies
  - 5+ electric shocks
  - 1,000,000 cycles
- And don’t mention the EMI
- Units sold for first flight heritage
Typical design point

- Propellant: 7 g Teflon
- Impulse bit: 50 uN·s⁻¹ (30-50% EMF)
- Specific impulse: 590 s
- Total impulse: 40 Ns
- ΔV: ~10 m·s⁻¹ for 4 kg @ 3 U

Astronet has indicated performance enhancements to improve design:

\[ \text{Obj} = \min(W \times \text{shocks}, (1-W) \times 1/\text{performance}, ...) \]
• Progression of ADCS capability
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CubeSats & debris mitigation
UK perspective

- NORAD TLEs provided for all satellites provide position accuracy to (0)km along track (to m using GPS if you can afford power)
- More CubeSats deorbited last year than were placed into orbit
- Sub-400 km (ISS) provides some difficulty in modelling due to aerodynamic uncertainty
- Most CubeSat RF system resonances make them highly observable to RADAR
- Under the Outer Space Treaty, appears that should an operator take control action to avoid a collision and collision occurs they will be liable (untested)
- < 0.1% of all debris are CubeSats at the > 10 cm range in LEO
- Most CubeSat operators comply with the 25 year IADC guidelines
But we must be responsible and ensure sustainability

https://www.planet.com/pulse/keeping-space-clean-responsible-satellite-fleet-operations/
Deorbit sail

• 0.3U total volume
• 1m² to 3m² sail area depending on mission requirement
• Can more than half the de-orbit time at end of life
• Automatic activation at mission end independent of spacecraft status
• Astronet work provided forwards looking for opportunities as solar sail
• Progression of ADCS capability
• Development of the uPPT product
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C3D Imaging

- CMOS radiation damage monitoring
  - Total ionising
  - Single event
- Narrow and wide field imaging
- Onboard image processing
  - Histogramic image rejection
  - Thumnailling and compression
- Technology demonstration of CMOS for future ESA missions, e.g. JUICE
Capturing images...

- Geolocating on a small satellite...

Algeria 9.26 am, 6\textsuperscript{th} November 2014
Limited, noisy, proxy telemetries
Pitch spin, precession and nutation characteristics still being assessed
What’s next

• Creating prediction software to inform
• Capture and downlink full size images
Looking forward
ESA/BISA atmospheric solar imager

PICASSO

- ESA/BISA mission
- 3U CubeSat designed, integrated and tested by Clyde Space
- Remote and in-situ measurements of Earth’s atmosphere
- Enhanced attitude control capability < 1 deg
- Reconfigurable autonomous data processing
- ESA grade science return
  - SLP: sweeping Langmuir probe
  - VISION: miniaturized hyperspectral imager
Gap filling ocean colour monitoring

Sea Hawk

- Matched instrument performance to SeaWiFS
  - 7 x ground resolution
  - Equivalent SNR performance
  - Spacecraft mass: 390 kg vs 4 kg
- Responsive acquisition to fill gap in global ocean awareness
- High data-rate downlink
  - 40 Mbps S/X Band capability
- Attitude, slew and payload stabilisation all key drivers
Low data rate ubiquitous global broadcasting

Outernet

• Robust global broadcast capability
  – Failure tolerant space segment
  – Frequency hopping roadmap

• Network resilience
  – Disruption-tolerant protocol for space-ground broadcast

• Differential drag for coarse orbit control
  – Constellation separation and management

• Scaling manufacturing capacity for constellations
  – Satellite batch production techniques
  – Standardised products and integration
  – Automated test facilities and procedures
Class leading submetre imaging capability

Earth Observation

- Submetre imaging using polarimetry and adaptive optics
  - 30 cm effective aperture
  - UK ATC hold novel patents and disruptive technology for processing
  - Progressing under UK government funding
- Designs for 12 U fixed and deployable 3 U variants
  - Resolution trade space from 2 m GSD based on mission SNR requirements
- Incorporating infrared and visible light detectors for a variety of applications

Uncooled uBolometer
Enabling missions
Future nanosatellite multi-role clusters

Efficient asset tasking & augmentation

Reconfigurable wideband spectrum monitoring

Secure key distribution

Rapid deployment & replenishment

Responsive comms

Resilient intersatellite networks

Proximity detection & operations

Hyperspectral imaging

Joint system-of-system networks

Multi-sensor target triangulation

Responsive commens

Distributed sensing & inferometry

Coarse orbit control, fine orbit knowledge

Space asset awareness

Rapid deployment & replenishment

Secure key distribution

Efficient asset tasking & augmentation

Reconfigurable wideband spectrum monitoring

Passive SAR
Maximising return
Themes overcoming nanosatellite constraints

COTS risk management

Responsive modular design & deployment

Reconfigurable data processing

Global networked intercompatibility

Swarms, formations & distributed networks

Deployable arrays, antenna & sensors

Significant dynamics & control elements

Advanced propulsion

Autonomous systems

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...and the iCubeSat trend
Precursor sales for interplanetary CubeSat missions

- NASA MRO will carry 2 interplanetary CubeSats for launch March 2016
- Proposals for CubeSats to contribute to all fields of interplanetary exploration and exploitation
- This is real: sales are supporting the talk
Typical future challenges

- Stabilising a payload to within 10 urad, using a coarse pointing platform and fine tracking payload with guidestar
- Optimising operations for an ad-hoc non-homogenous constellation with coarse orbit and attitude control to maximise utility (clusters, formations, docking)
- Deployment and manoeuvres of highly constrained interplanetary CubeSats considering the CR3BP
- Meeting (moral) obligations for sustainable space access: what is a proportionate deorbit / safety plan for a given orbit space
- Combine ad-hoc delay tolerant networking with astrodynamics and implement for autonomy in low performance distributed satellites
How to facilitate collaboration?
NANOBED Mission Lab

• NANOBED Mission Lab was proposed as a fellowship to the Royal Commission for the Exhibition of 1851
• Satellite Applications Catapult identified project as strongly supportive of their goals, seed funded setup of two facilities at Strathclyde and Harwell
• Numerous facilities and collaborations in discussion internal within the UK: proven demand
• Plans to go international next month with announcement of our first overseas partner
Conceptual features

MISSION TECHNOLOGIES

SYS
STACK

OBSERVATION AREA

OPS
FLATSAT

STORAGE

CLEAN AREA

PI
Mission lab concept

- Rapid integration, demonstration, and characterisation of payloads with platform
- System design tools and processes to enable rapid generation of mission design points
- Demonstration of emerging low-cost technologies as novel mission or enabling technologies (experiment showcase)
- Facilities / space for a potential PI to use in line with payload protocol process, including remote access
- No manufacture or EVT (post-TRR) facilities: system development up to functional check but feed through
- Network organisation of site across UK and world for collaboration: international partnership TBA imminently
- Supports throughlife and concurrent CubeSat development philosophy: collocation of team for integrated design
Quantum Technology

- Lead in QKD application for secure telecoms follow on capabilities
  - Highly miniaturised atomic clocks
  - Enhanced metrology -> improved GNS
  - Fundamental physics experiments: gravity waves, inertia
Supporting emergent nanosatellite mission applications

Demonstration of NANOBED Harwell @ Satellite Applications Catapult

NANOLED adds 3DP capability!

3DP is an exciting technology in all fields, but the potential for space is especially so. We are prototyping the capability at NANOLED Strathclyde allowing our developers to 3D print their designs directly from the CAD design tool. Why? Typically, and despite advances made by developers around modularity, satellite integration is a complex challenge from [].
MOEA Multidisciplinary Design Optimisation

(1) DESIGN

(2) ASSESS

(3) OPTIMISE
Conclusions

• Without the support of Astronet and Strathclyde, our progress and knowledge and direction in dynamics would be reduced
• Imposing nanosatellite design constraints can drive innovation in a cost-limited space and lead through to more rapid in-orbit validation
• Given constraints and costs of nanosatellites, having some hand-on experience of satellite technology is useful for analysts and applied mathematicians: we will continue to work to bridge gap
• The space sector has many locally optimal market spaces, we seem to have found one (is it stable?!)  
• By incorporating advanced dynamics and astrodynamics we can drive forward capability
• Nanosatellites and their development philosophy are part of our future, lets push the boundaries together
Thank-you
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NANOBED Missions Lab Beta Website: www.craftprospect.com/nanobed